

SUPERNOVAE AND CALIFORNIUM 254*

W. BAADE, G. R. BURBIDGE, AND F. HOYLE†

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

AND

E. M. BURBIDGE, R. F. CHRISTY, AND W. A. FOWLER

Kellogg Radiation Laboratory
California Institute of Technology

Baade and Minkowski have shown that on the basis of the observed light curves and spectra we have to distinguish two kinds of supernovae. Most remarkable are the light curves of the supernovae of type I. About 100 days after the maximum the decrease in brightness becomes linear with a gradient of 0.0137 magnitude per day.¹ This linear decrease with the gradient given above applies both to the observed photographic and visual light curves. An example of the former is the light curve of the supernova in IC 4182 which could be followed by Baade until it reached the 20th magnitude (Fig. 1). Examples of visual light curves—of

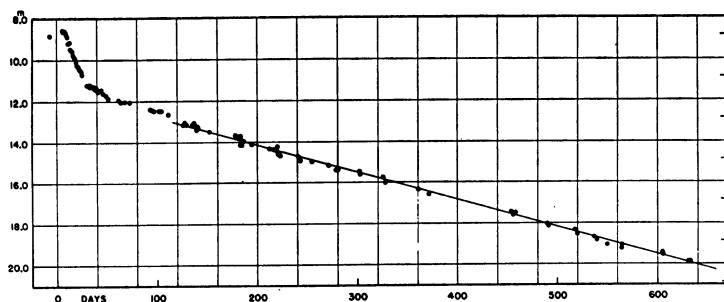


FIG. 1.—Photographic light curve of the supernova in IC 4182. The abscissa gives the time after maximum, in days; the ordinate gives the apparent photographic magnitude.

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† Normally at St. John's College, Cambridge, England.

B Cassiopeiae (1572) and SN Ophiuchi (1604)—are given in the paper already cited. B Cassiopeiae was observed up to 460 days past maximum, the supernova in IC 4182 up to 640 days. The linear decline implies that the light intensity decays in an exponential manner, and the observed rate indicates a half-life of 55 days \pm 1 day. Although the curve for the supernova in IC 4182 extends over more than ten times this half-life, there is no deviation from a strictly exponential decline.

In a paper which has been submitted to the *Physical Review*,² a theory of supernovae of type I has been proposed, and we wish to give here a brief summary of this work.

As Borst has already pointed out,³ it is difficult to suggest any energy source other than the decay of a radioactive nucleus which would give an exponential decline, especially since the half-life is accurately the same for different type I supernovae. He suggested that the isotope of beryllium with mass 7 might be responsible, but other radioactive isotopes which also have half-lives near or equal to 55 days, and which might therefore provide the energy supply, are strontium 89 and the transuranic element californium 254, recently reported by Fields *et al.*⁴

The total energy emitted in a supernova outburst is of the order of 10^{49} – 10^{50} ergs, but the major part of this is emitted in the first few days, and by integrating under the linear part of the light curve we have estimated that the energy emitted during the exponential decay is about 10^{47} ergs. Consideration of the energy released in the decay of the three possible radioactive nuclei, and hence the amount of these isotopes required, as well as other arguments concerning the way in which they can be synthesized, strongly suggest that Cf^{254} is the most likely to be responsible for the energy in the decay portion of the light curve. A major reason for this is that, whereas Be^7 and Sr^{89} decay by capturing or emitting an electron, respectively, and release convertible energies of the order of 0.1–1 Mev, Cf^{254} decays by spontaneous fission, and the amount of energy released, which is mainly in the kinetic energy of the fission fragments, is about 200 Mev. This means that only about 10^{29} grams of Cf^{254} must be synthesized in order to release the necessary 10^{47} ergs.

Cf^{254} has been synthesized terrestrially in the thermonuclear

explosion of November 1952, by the bombardment of uranium by an instantaneous flux of neutrons. If this isotope is to be built in a supernova outburst, a large flux of neutrons has to be produced, which would then be captured mainly by the elements in the "iron peak" in the cosmic abundance curve, the most plentiful of which is Fe itself. The build-up would be carried to Cf by successive neutron capture and beta decay.

It is probable that the Cf^{254} would be produced in the region extending inward from the photosphere toward the core. This region should, on this theory, consist of approximately equal numbers of protons, alpha particles, C^{12} , O^{16} , and Ne^{20} nuclei, with an abundance of Fe equal to about 10^{-3} times the abundance of the light nuclei. This means that the star is in an advanced evolutionary stage and is very deficient in hydrogen, and that the alpha particles and light nuclei have been synthesized in the deep interior of the star^{5,6,7} and then mixed by a relatively slow circulation process. The Fe abundance, however, is that present at the time of formation of the star.

It is supposed that the temperature in the outer part of the stellar interior is raised initially to about 10^8 degrees, by the release of gravitational energy through the implosion of the central regions of the star, which is, in this point of view, the origin of the supernova outburst. This increase in temperature will lead to the onset of (p, γ) reactions (protons being captured by light nuclei with the emission of gamma rays); in such reactions the mean energy release is about 2 Mev per proton. The total energy production is then about 10^{17} ergs/gram. This energy will both heat the material and also escape, partly in the form of radiation; it is ample to account for the total radiant energy emitted in the outburst. If more than 10^{16} ergs/gram is preserved in kinetic energy of expansion, then velocities ≥ 1000 km/sec are to be expected; these are of the order of those observed now in the Crab Nebula.

The dimension of the envelope before the outburst is probably smaller than the radius of the sun, perhaps about 10^9 – 10^{10} cm. Thus the time scale of the explosion is in the range 10–100 seconds. Na^{21} will be produced by the (p, γ) reaction on Ne^{20} , and will decay to form Ne^{21} . At the high temperatures produced by the release of 10^{17} ergs/gram, the reaction in which Ne^{21} captures an

alpha particle, with the emission of a neutron, occurs very fast; thus approximately one neutron per Ne nucleus will be produced. These will be sufficient to provide the two hundred neutrons per Fe nucleus which are necessary to build up to Cf^{254} . Possible reasons why the neutron-capture process should lead to a large production of this particular isotope, and why its decay should dominate all other energy sources in the declining portion of the light curve, lie in the systematics of nuclear fission and other properties of these heavy nuclei. Shell structure effects make Cf^{254} the only nucleus with a half-life of 55 days (or near it) which decays by the energetic fission process rather than by low-energy alpha-particle emission.

The problem of the physical conditions in the expanding supernova shell is one of great complexity, particularly since the visible radiation is apparently not thermal in origin. No satisfactory identifications of any of the spectral features of type I supernovae have been made, apart from the narrow emission lines of $[\text{O I}]$.⁸ One possibility which was suggested was that the material in the outer envelope during the decay might be cool enough for the C, N, and O to occur in molecular form, so that some of the broad features might be molecular bands.

It is possible that supernovae of type II are the result of similar explosions in stars which do not have a large deficiency of hydrogen in the envelope. In this case no neutrons will be produced since Na^{21} is converted into Mg^{22} before it can decay, and hence Cf^{254} will not be synthesized, so that the characteristic type I light curve with its 55-day half-life would not be expected. However, a large amount of energy will be released through (p, γ) reactions. This is probably sufficient to account for the high surface temperatures and also the large observed explosive velocities (~ 5000 km/sec).

The terrestrial production of Cf^{254} is evidence for the production of heavy elements by neutron capture processes on a fast time scale, just as Tc^{99} is evidence for neutron capture at a slow rate in red giant stars. The arguments presented in the paper² summarized here suggest that this process can happen on a cosmic scale, and has contributed to the synthesis of the heavy elements in stars.

We are indebted to Dr. R. Minkowski for helpful discussions of the spectra of supernovae.

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³ L. B. Borst, *Phys. Rev.*, **78**, 807, 1950.

⁴ Fields, Studier, Diamond, Mech, Inghram, Pyle, Stevens, Fried, Manning, Ghiorso, Thompson, Higgins, and Seaborg, *Phys. Rev.*, **102**, 180, 1956.

⁵ E. E. Salpeter, *Ap. J.*, **115**, 326, 1952.

⁶ F. Hoyle, *Ap. J. Supplements*, **1**, 121, 1954 (No. 5).

⁷ W. A. Fowler, G. R. Burbidge, and E. M. Burbidge, *Ap. J.*, **122**, 271, 1955.

⁸ R. Minkowski, *Ap. J.*, **89**, 156, 1939.